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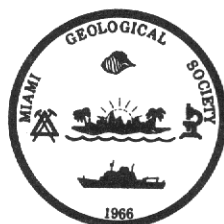Edited by

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INTERPRETATION OF GRAVITY ANOMALIES, MASAYA CALDERA COMPLEX, NICARAGUA

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ABSTRACT

The Masaya Caldera Complex, Nicaragua, has been the site of major explosive and effusive eruptions in the Quaternary and remains active today. We have interpreted gravity data collected during a regional gravity study by R.L. Williams (1972) in an effort to further delineate geologic structures associated with this unique volcanic feature. A total of 217 gravity stations were occupied in the vicinity of Masaya caldera. Several large amplitude gravity anomalies occur in the area, including a broad +35 mgal high centered on the NE side of Masaya caldera. Upward continuation of the gravity data reveals that this anomaly is similar in shape to the caldera itself: elongate approximately N60°W, parallel to the strike of the Nicaragua Depression, and that it is caused by an anomalous mass located at high levels in the crust. A two and one-half dimensional gravity model suggests that the anomaly is produced by a thin, plate -like body, of density contrast between 300 and 500 kg/m^3. We believe the anomaly is caused by an igneous intrusion, possibly a laccolith or sill, which is approximately 17 km long, 6 to 7 km wide, 2 km thick, and buried at a depth greater than 0.5 km. This body is offset from the caldera and probably intruded prior to the formation of the active caldera. Its presence indicates that the locus of activity has shifted over time, and that volumes of magma, similar to those required by current outgassing models, have intruded to shallow levels previously. Other, negative gravity anomalies occur near the active crater and may be caused by the presence of magma beneath the active crater, conduit geometry or a thick accumulation of tephra.

INTRODUCTION

The Masaya Caldera Complex, Nicaragua (11.98°N, 86.15°W) is an unusual center, which has been very active since the first European exploration of Central America. The shield-like form and fluid basaltic lavas are quite unlike those found at other Central American volcanoes (McBirney, 1956; Mooser et al., 1958; and Simkin et al., 1981). The caldera is well-defined by near vertical bounding faults of zero to 250 m relief and measures approximately 12 x 5 km, elongate in a N60°W orientation, parallel to the axis of the Nicaraguan Depression. Recent volcanic activity at Masaya has been focused at several small pit craters, within the caldera. Santiago Crater, which was formed in 1853 (S.N. Williams, 1983a), is the current site of degassing and extrusive activity. Recent detailed geological and volcanological studies have demonstrated that Masaya has also been the site of at least two Plinian eruptions in the Quaternary (S.N. Williams, 1983b). The latest episode of activity (since late 1979) has involved energetic degassing, through an old lava lake within the Santiago Crater, of a subjacent intrusive mass (Stoiber et al., 1986) and, most recently, the formation of a new lava lake (Cruesot et al., 1989).

The utility of gravity data as an aid in the interpretation of volcanic structures and activity has been amply demonstrated (Yokoyama, 1972; Tsuboi, 1983; Rymer and Brown, 1984; Rymer and Brown, 1986; Brown et al., 1987; and Eggers, 1987). Our recent work at Masaya volcano (Crenshaw et al., 1982; S.N. Williams, 1983a; S.N. Williams, 1983b; Williams and Stoiber, 1983; Stoiber et al., 1986; Walker and Williams, 1986) has established the importance of shallow intrusive magmatic activity and long-term degassing processes at Masaya. In an effort to further improve our understanding of intrusive magma volumes and to delineate geologic structures associated with this major volcanic feature, we have interpreted gravity data collected as part of a regional gravity study by R.L. Williams (1972).

In the gravity study by Williams, a total of 217 stations were occupied in the vicinity of Masaya caldera. Thirty-one stations are located within the caldera itself. Most of these gravity
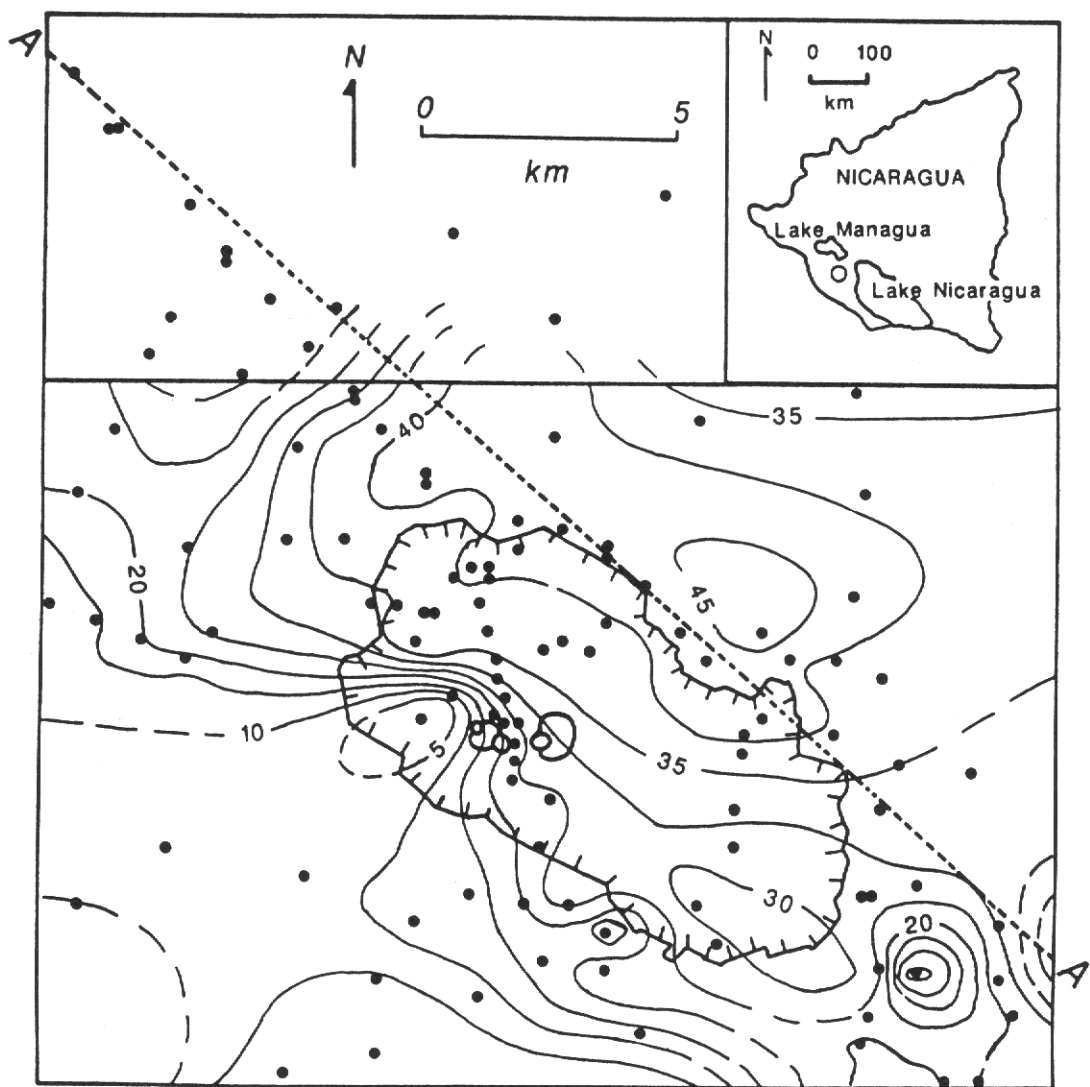
Figure 1. Complete Bouguer anomaly map of the Masaya caldera complex and surrounding area. The contoured area (south of solid line) was contoured using a finite-difference minimum curvature interpolation algorithm (Briggs, 1974). Gravity contour interval is 5 mgal and values are relative to the Managua International Airport station (R.L. Williams, 1972). Gravity stations are shown as solid circles. In this and following figures, the caldera-bounding faults are indicated by solid hachured lines and Santiago and other Recent craters within the caldera are outlined. Profile A-A'; is drawn and modeled in Figure 4. Inset: Nicaragua, with the location of Masaya Caldera Complex indicated by the open circle.

stations are located along roads that transect the area; many of the stations were occupied twice. Line leveling and barometric altimetry provided elevation control for this survey and gravity data were reduced to the complete Bouguer anomaly by R.L. Williams (1972).

GRAVITY ANOMALY MAPS

We utilized these data over an area of approximately 25 x 15 km, centered on the caldera (Figure 1). The data were interpolated to a 50 x 50 grid using a minimum curvature algorithm and contoured (Briggs, 1974; Snyder, 1978). Despite the low sampling density, several large-amplitude gravity anomalies are immediately apparent (Figure 1).
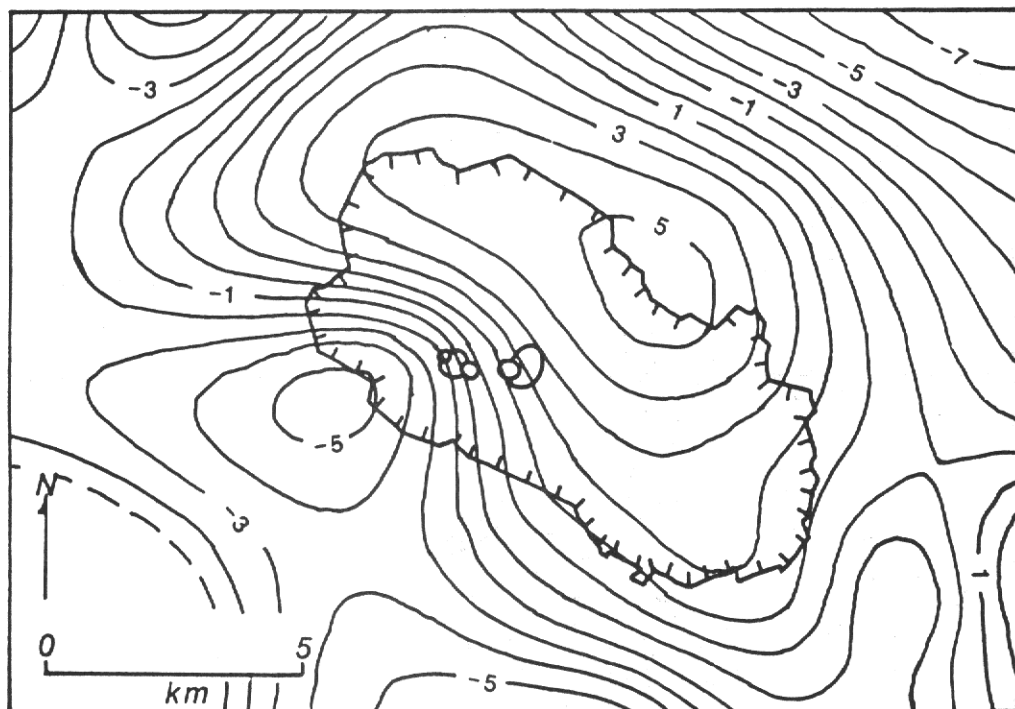
Fig. 2. Upward continuation by 1500m of the interpolated gravity values clarifies the board, large-amplitude anomaly centered on the northeast wall of Masaya Caldera. A best-fit plane was removed prior to making the upward continuation. This continuation was done in the frequency domain using the methods and algorithm of Hildebrand (1983). Contour interval is 1 mgal.

As an aid to the interpretation of these anomalies, a best-fit plane was removed from the interpolated grid and the residuals were upwardly continued (Figure 2). Upward continuation acts to attenuate short-wavelength anomalies caused by local, shallow features. In this case, upward continuation to 1500 m has the effect of isolating a broad positive gravity anomaly, centered on the northeast boundary of the caldera. This positive anomaly is based on a large number of data points and is thought to be a robust signature. Even this anomaly is much attenuated and essentially disappears when the data are upwardly continued to 2500 m, indicating that the source of the anomaly is located at high levels in the crust. A negative anomaly located on the southwest corner of the caldera is only supported by one data point and cannot be treated with as much confidence. The shape and scale of the NE anomaly is like that of Masaya caldera itself, i.e. the anomaly (Figure 2) is elongate approximately N60° W, parallel to the strike of the Nicaragua Depression.

Near-surface, local anomalies were isolated by wavelength filtering. A high-pass, ramped filter was constructed such that anomalies at wavelengths longer than 6 km were strongly attenuated (Figure 3). Of note is a negative anomaly with an amplitude of approximately 15 mgal, located immediately NW of the Santiago Crater. Although the true extent of this anomaly cannot be well constrained from the data (Figure 1), it is clear that a mass deficiency was present here at the time of this survey.

GRAVITY MODEL AND INTERPRETATION

We created a two and one-half dimensional gravity model along a 27 km-long traverse (A-A', Figure 1) near which there is a relatively high density of gravity stations. In two and one-half dimensional modeling, the model is taken as having a finite length perpendicular to the profile, rather than infinite length in this dimension, as assumed in two dimensional gravity modeling (Webring, 1985). The profile, A-A', transects the positive gravity anomaly near the NE rim of the caldera. Gravity values from stations located up to 1.5 km from the traverse line were projected onto the plane of the profile and 9 mgal were subtracted from the value recorded at each station so that the value of the station at point A (Figure
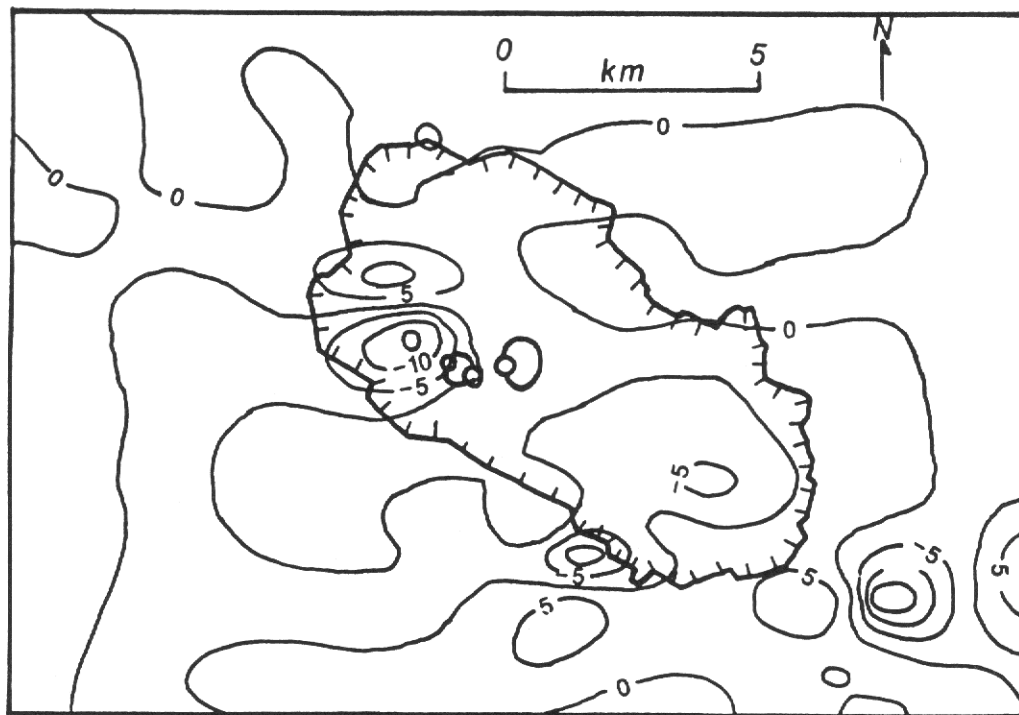
Fig. 3 Filtering the interpolated gravity values using a high-pass filter isolates a 15 mgal negative anomaly, located NW of the Santiago crater. Filtering was done in the frequency domain using a ramp filter: wavelengths greater than 7 km are completely removed, wavelengths less than 5 km are passed. Contour interval is 5 mgal.

1) was zero mgal. The profile and accompanying model are illustrated in Figure 4.

In order to constrain the gravity model, we have incorporated several geologic features into it. The regional geology near Masaya caldera consists of a sequence of Tertiary and younger interbedded lava flows, pyroclastics, and volcanogenic sediment which are generally termed the Las Sierras Formation. The total thickness of this sequence is unknown, but it is at least 600m thick in some locations (Bice, 1980), The details of the stratigraphy and origin of the Las Sierras formation await future studies but it is thought that at least part of the deposits were erupted from Masaya, some as recently as 29,200±200y.b.p. (Williams, 1983a). The detailed geological study of the caldera conducted by one of us (SNW) produced evidence that the present caldera formed as a result of a single catastrophic collapse event triggered by the eruption of voluminous ignimbrites and pyroclastic surges of basaltic composition. The timing of caldera formation is constrained by carbon-14 ages determined on organic debris within the regionally extensive surge deposit (known as the El Retiro in Managua (Bice, 1980) to be between

2,250 and 6,500 y.b.p. After formation of the caldera, renewed magmatism caused the infilling and ultimately, in some areas, overfilling of the caldera with younger lava flows. Eruption rates average from 1.9-5.5 x 10^6 m^3/year, to produce a total erupted volume of lava flows of about 14 km^3 (Williams, 1983a). The historic record of activity at Masaya indicates quite a different character, being dominated by active degassing of large volumes of magma which are rarely or never erupted. The historic eruption rates have been about 0.07 x 10^6 m^3/year or only 1/20 to 1/60th of the recent record. Our data on the total flux of sulfur dioxide (Stoiber et al., 1986) released during the 1979-1987 degassing crisis, combined with the historic record, allows us to calculate that there has been intrusion of approximately 10 km^3 of degassed magma during the past century alone. That could amount to a sill-like body of 180 m thickness, beneath an area equal to the caldera or a sphere of radius 1.3km (for comparison, the diameter of the Santiago Crater (from which all of the most recent degassing emanated) is about 600m).
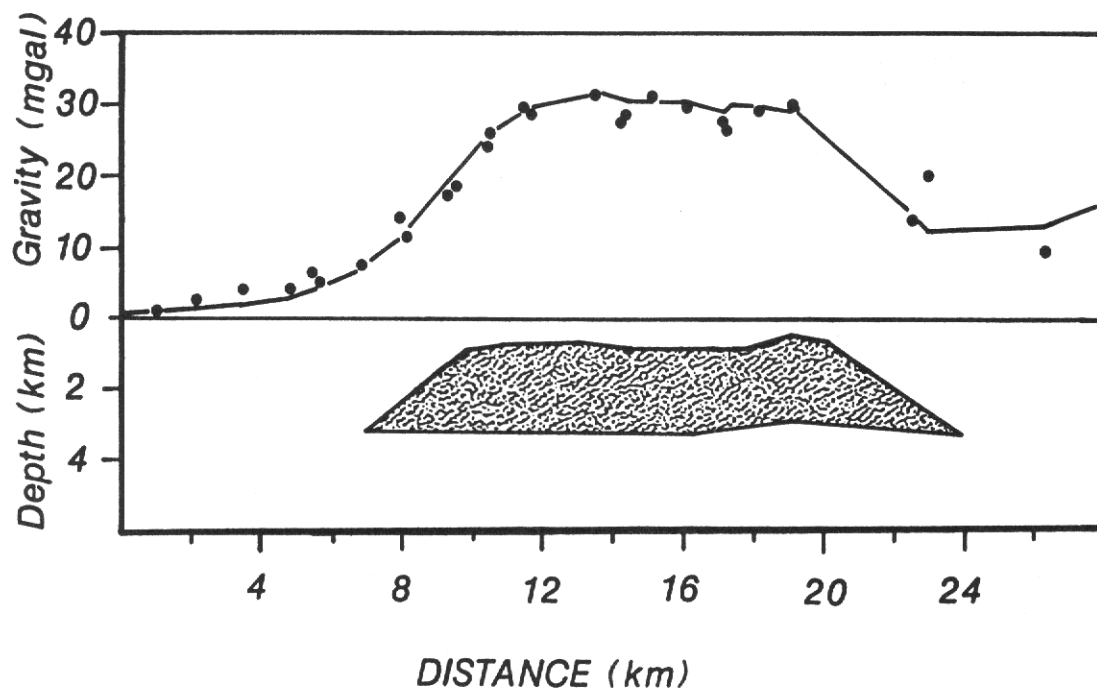
Fig. 4 Observed gravity values (open circle), model of anomalous mass distribution (shaded polygon), and calculated gravity profile (solid curve) along traverse A-A' (Figure 1). In this model, the density contrast between the anomalous mass and surrounding rock is +500kg/m^3. The profile was calculated using the algorithm of Talwani and Ewing (1960) and programs of Webring (1985) and CBC.

No surface geologic contact are readily associated with the broad positive gravity anomaly (Figures 1 and 2), shown in profile in Figure 4. That fact, combined with our knowledge of the geological makeup of the caldera walls convince us that the profile (Figure 4) is most realistically modeled using a completely buried anomalous mass. Regional NW-SE faults, associated with the Nicaraguan Depression, can be projected through Masaya caldera. Strong N-S faulting, related to the location of the caldera at the eastern margin of the central Nicaragua segment boundary (Stoiber and Carr, 1974), is obvious to the north of the caldera, where surficial deposits are offset, and to the south, where vents are aligned in rows. Although there is no vertical displacement of rocks due to regional faults within the caldera, the presence of strong N60°W oriented structures is suggested by the alignments of vents on the caldera floor and the distribution of soil geochemical anomalies within the caldera (Crenshaw et al., 1982). These regional faults may affect gravity gradients, but their affect on the NW-oriented profile should be minimal.

Figure 4 is the one of many models which were considered in our efforts to explain the observed gravity anomaly along traverse A-A'. The key elements of this model are the requirements for a high density contrast (500 kg/m^3) and the thin, plate-like geometry of the anomalous mass. This plate is approximately 17 km long, 2 km thick, and buried below a depth of approximately 0.5 km. The model is most sensitive to the geometry of the plate ends. The presence of the steepest gravity gradient near the crest of the anomaly requires that the contacts dip away from the center of the anomalous mass. This is particularly true on the NW flank of the anomaly, where control is best. Modeling of less well-constrained profiles perpendicular to A-A' indicates that the plate is 5-7 km wide. The model illustrated in Figure 4 uses a model width of 6 km. Finally, a rectangular prism has been added beneath Apoyo caldera, immediately SE of the map area, to account for a regional increase in gravity from NW to SE.

If, as an alternative, an anomalous mass having a density contrast of 300 kg/m^3 is considered, the plate must extend from the present surface to a depth of 5 km. The plate has a length of approximately 20 km and must taper upward, as in the previous model. It is not possible to model the steep gradient observed in the profile with density contrast smaller than 300 kg/m^3.

EXCESS MASS CALCULATION

The excess mass producing the observed gravity anomalies can be computed directly from the gravity observations without assuming that the shape of the causative body is known (eg: Tsuboi, 1983). This involves the application of Gauss's Theorem:

$$E = \frac{1}{2\pi G} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x,y) \, dx \, dy$$

where E is the excess mass, G is the gravitational constant, and g is the measured gravity anomaly. In this case, the best-fit plane was removed from the observed data and positive residuals were used in the calculation. A grid slightly larger in area and grid point spacing was used, compared to that used in previous calculations. This requires greater interpolation, especially north of the map area (Figure 1), but also provides greater closure about the positive anomaly. The excess mass, calculated in this manner, is 2.9 x 10^{10} metric tons. Given an excess density of 500 kg/ m^3, this corresponds to an excess volume of approximately 116 km^3.

The volume of the model found by forward calculation (Figure 4) is approximately 168 km^3, which is 30% greater than the volume inferred from the excess mass calculation. This disparity may be accounted for in several ways. Most likely, the anomaly is not wholly represented by the residual values, after a best-fit plane is removed; alternatively, the interpolation of gravity values on the north side of the map area may not be adequate. Nonetheless, the general agreement between the model and the excess mass calculation suggests that the predicted mass and size of the causative body is reasonably accurate.

DISCUSSION AND CONCLUSIONS

Gravity anomalies of substantial amplitude and wavelength are found within and around Masaya caldera. Although we have interpreted a regional data set, some patterns in the data do emerge. Filtering the data by upward continuation and wavelength filtering enhances large broad anomalies and local anomalies, respectively. The large-scale feature (Figure 2) is a positive anomaly whose magnitude (35mgal) and wavelength (15km) is quite similar to those found at other basaltic volcanoes from a variety of tectonic settings (e.g. Finn and Williams 1972; Rymer and Brown, 1986), but considerably smaller in magnitude and shorter in wavelength than gravity anomalies associated with shallow (<10 km deep) intrusions at the Hawaiian shields: Kilauea, Mauna Loa, and Mauna Kea (Hill and Zucca, 1987). The long-wavelength anomaly identified at Masaya is not like the positive anomalies found at some andesitic Central American stratovolcanoes, which have shorter wavelengths and generally smaller amplitudes (Brown et al., 1987).

The most surprising result of our analysis is that the large positive anomaly is not concentric with respect to the caldera nor is it contained within the caldera structure, as has been often observed at other calderas for which such data exists (Rymer and Brown, 1986). Upward continuation has demonstrated that the broad positive gravity anomaly is actually offset slightly northward from Masaya caldera itself and is of similar shape. This means that despite the presence of a thick section of caldera-fill of fluid lavas and minor tephra and flow breccia within the caldera, another cause must be responsible for the dominant large-scale anomaly. The steep gravity gradients require a relatively near-surface source. We believe this anomaly (Figures 2 and 4) is likely to be of igneous origin. The geometry of the causative body suggests that it is either an intrusion, possibly a laccolith or sill, or a series of lavas, which have accumulated to substantial thickness over a limited area. A density contrast of 300 to 500 kg/m^3 argues in favor of an igneous intrusions because intrusive igneous rocks have considerably higher densities than the lavas and tephra of the caldera and caldera wall.

If the causative body is an igneous intrusive, similar to those inferred from the history of extraordinary degassing at Masaya (Stoiber et al., 1986), then a volume of 100 to 200 km^3 could

500

have accumulated in a time frame as short as 1,000 to 2,000 years, during which time the magma may have degassed in a manner similar to that observed historically. It is unlikely, however, even if the anomaly is caused by an intrusion, that it is related to modern activity of Masaya because the anomaly is not concentric with the caldera margin, the high density contrast suggests that the anomaly is caused by solid, rather than molten or partially molten rock, and because no surface deformation or other volcanic features can be unambiguously related to the causative body. For these reasons we believe that the intrusion occurred before the formation of the present caldera. The details of the shapes of the 35 and 40 mgal contours over the caldera walls (Figure 1) are consistent with the possibility that the intrusive body is downthrown by these faults, but greater sampling density is required to adequately test this supposition.

The presence of short-wavelength and large amplitude negative gravity anomalies within the caldera is suggested by measurements at several stations. One of these anomalies is located immediately NW of the active Santiago crater, and may be caused by conduit geometry or the presence of magma at shallow levels. Unfortunately, this anomaly is not tightly constrained by the data. We do know that this location corresponds to the presence of a young open eruptive fissure, which extends from the NW lip of the San Pedro crater (the small older crater which lies on the western edge of the Santiago-Nindiri-San Pedro complex) for at least one km and from which a lava flow emanated (probably within the past 1,000 years). A clearer interpretation of the significance of that anomaly would require more closely-spaced data for that region. However, the negative anomaly is also near a point on the caldera margin which has consistently and exclusively received the deposition of scoriaceous tephra for the entire history of the present Masaya caldera. This results from the extremely consistent tradewinds which blow at the latitudes of Nicaragua. The plinian deposits shown to have been erupted from Masaya about 30,000 years ago (Williams, 1983b) are accumulated to unusual thicknesses in this location. If those same processes have persisted over longer times, the gravity low could be caused by a major accumulation of uncompacted low density tephra. The presence of the anomalies described in this work suggests that future geophysical work at Masaya may be expected to yield further insight into the volcanic processes operating beneath this caldera.

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